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EVALUATING THE EFFECTIVENESS OF ACTIVE NOISE REDUCTION IN FLIGHT HELMETS

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ABSTRACT

This study was carried out to investigate laboratory procedures appropriate for measuring the effectiveness of active noise reduction (ANR) devices. The procedures were: ear-canal measurements using an acoustic test fixture (ATF)(an objective procedure), and masked-threshold and loudness-balance tests (psychophysical procedures). In addition, the effect of ANR on signal detection and speech reception was investigated. The results do not clearly permit one procedure to be recommended for the evaluation of ANR systems. Signal detection performance and speech intelligibility may be used, but the results are specific to the acoustic environment of the listener and the detection task or speech-system parameters of the evaluation. When the attenuation of the ANR system is measured objectively with a transducer inside the earmuff/ear-canal volume, the location of the transducer affects the observed ANR attenuations.

INTRODUCTION

The advent of high powered fixed- and rotary-wing aircraft and tracked armoured fighting vehicles (AFV) has increased the level of noise to which crews are exposed. This in turn increases the potential for hearing loss and degrades aural communication. Although noise-excluding ear muffs incorporated into either a helmet or headset are usually worn, they are renowned for their limited passive attenuation at low frequencies. Among current flight helmets, mean attenuations at 125 and 250 Hz are limited to about 13 dB (see Appendix A).

Active Noise Reduction (ANR) offers a means of increasing the attenuation at low and mid frequencies. It relies on sensing the sound inside a circumaural device and cancelling it by means of negative feedback through a miniature speaker inside the enclosed volume. ANR could be incorporated in future flight and combat-vehicle helmets and headsets to compensate for the excess noise that would otherwise mask audio displays and speech signals, and would pose a hazard to hearing. The concept is not new; a patent was issued for an ANR device in 1936 [1] and the possibility of reducing noise actively in a finite space within a free field was investigated in 1953 by Olsen and May [2].

In the mid 1950s, research and development work was initiated for the U.S. Air Force and Army Signal Corps to apply the principle of ANR to communication headsets [3,4]. Development programs were also undertaken during the 1960s for the U.S. Army Electronics Command for an ANR system to be used in the SPH-4 helmet [5]. The improvement in attenuation provided by these early developments was limited to a maximum of about 10 dB, the peak in noise reduction occurring below 1000 Hz.

In 1975, development of an ANR system for the RAF Mk 4 helmet was commenced at the Institute of Sound and Vibration Research, University of Southampton, under contract from the UK Ministry of Defence (Procurement Executive) [6]. In 1978, the feasibility of an ear-canal ANR system was studied by Bell-Northern Research (Ottawa) under contract from DCIEM [7]. With this system, 9.5 dB in noise reduction was achieved with maximum attenuation occurring between 1000 and 2000 Hz. It was concluded that any improvement in the ear-insert system required the application of adaptive filtering to accommodate rapid changes in operating conditions and more effective electroacoustic transducers.

Since 1982, the U.S. Air Force has supported the development of an ANR system by Bose Corporation [1]. Prototypes have been test flown in a variety of rotary- and fixed-wing aircraft, and most recently, in the around-the-world endurance flight of *Voyager* [8]. Two U.K. firms (Racal Acoustics [9] and Plessey [10]) have also developed ANR systems which are in the pre-production stage. It is intended that in the near future these systems will be introduced into British AFVs.

OPERATING PRINCIPLE OF ANR

A block diagram illustrating the principle of operation of current ANR systems is given in Figure 1. This system utilizes an analogue electroacoustic feedback circuit to cancel the noise $N(t)$ penetrating the ear cup. The instantaneous sound pressure under the ear cup is sensed by a miniature electret microphone, the signal from which is passed through a phase compensation filter and returned out of phase to the enclosed ear-cup/ear-canal volume. The resulting sound pressure at the ear $P_e(t)$ is the resultant of $N(t)$ and the cancelling signal coming from the earphone S_1. That is,

$$P_e(t) = N(t) - P_e(t)(G_1 G_2 S_1 S_2 K)$$

$$P_e(t) = \frac{N(t)}{1 + G_1 G_2 S_1 S_2 K} \qquad (1)$$

where G_1 and G_2 are the gains of the drive amplifier and phase-compensation filter, and

S_1, S_2 and K are the electroacoustic sensitivities of the earphone and sensing microphone and the acoustical characteristics of the enclosed volume under the ear cup respectively[6].

The feedback-loop gain $G_1G_2S_1S_2K$ determines the amount of noise reduction achieved for $G_1G_2S_1S_2K >> 1$. The product of the terms S_1S_2K represents the combined electroacoustic response of the earphone/enclosed-volume/sensing-microphone, and varies with frequency, the shape and size of the ear canal, and any leakage between the ear cup and the circumaural surface. Hence the loop gain is also frequency dependent, and noise reduction is limited generally to frequencies below 2000 Hz. When $G_1G_2S_1S_2K < 0$, noise enhancement rather than reduction is obtained.

Loop gain cannot be too high, otherwise when $G_1G_2S_1S_2K = -1$, the system will oscillate. Stability can be restored by reducing the gain G_1 of the drive amplifier and/or tuning the filter G_2 to correct for phase-delay distortion. In practice, the phase-compensation filter is tuned to maximize noise reduction for a specific noise spectrum.

The intercom signal $S(t)$ is also affected by the feedback. To counter this and provide some signal enhancement, intercom-signal pre-emphasis is accomplished as shown. Accordingly, the sound pressure due to $S(t)$ is given by:

$$P_s(t) = \frac{S(t)G_1S_1}{1 + G_1G_2S_1S_2K}. \qquad (2)$$

The effectiveness of ANR is specified by the noise reduction obtained in the enclosed ear-cup volume as a function of frequency. It is determined most readily in a diffuse sound field (the ANR/ear muff is worn by a subject) by measuring with a miniature (probe) microphone the difference in sound pressure level (SPL) at the entrance to the wearer's ear canal when the ANR system is *ON* and *OFF*. This method yields a measure of the noise reduction at a position away from the wearer's eardrum, and can produce variations in measured ANR effectiveness as a result of differences in microphone position. This problem can be overcome with an acoustic manikin having a simulated ear canal terminated with the correct acoustic impedance and an eardrum microphone. However, an alternative method would also include the ANR/ear-muff wearer in the measurement using a psychophysical procedure to give an estimate of the variability of the noise reduction within and between users.

The intent of this study was to investigate laboratory procedures appropriate for measuring the effectiveness of ANR devices. The device studied was a prototype ANR system designed by the Royal Aerospace Establishment, UK Ministry of Defence, fitted into the ear cups of a Helmets Limited (UK) Advanced Lightweight Protective Helmet for Aircrew (ALPHA) with foam-filled seals, and loaned to DCIEM under the auspices of The Technical Cooperation Panel (TTCP), Subgroup H Technical Panel 6. The phase compensation filter in the RAE prototype was tuned to minimize noise enhancement above 1000 Hz, which resulted in reduced noise cancellation below 1000 Hz. The flight helmet was a *Medium-Broad* size, and contained individual ANR systems for each ear.

MEASUREMENT PROCEDURES

One objective and two psychophysical procedures were used to evaluate the attenuation offered by the ANR system: ear-canal measurements using the Acoustic Test Fixture (ATF) developed under contract for DCIEM; noise-masking threshold shifts; and loudness-balance tests. In addition, the effect of ANR on signal detection and speech reception was investigated.

In the masking and loudness-balance procedures, the bandwidths of the noise were chosen to encompass the equivalent rectangular bandwidths (ERB) of the human peripheral auditory filter [11] at 63, 125, 250, 315, 500, 630, 800, 1000 and 1600 Hz. The ERB exceeds the one-third octave band at 63 Hz, is equal to it at 125 Hz, and is less at

the other frequencies (see Appendix B). Accordingly, the one-octave bandwidth was used at 63 Hz and one-third octaves were used at the other test frequencies.

A. *ATF Measurement Procedures*

The ATF is comprised of: (1) a head unit in two symmetrical left and right halves, cast from a commercially available KEMAR original *, and made of a hard aluminum-filled epoxy to give the correct dynamic mass and required eardrum-microphone isolation, (2) a new compliant neck to simulate the translational vibrations of the human head in a sound field, and (3) a pentagonal-shaped cavity in the left half of the head unit that can accommodate an insertable ear module [14]. All other features of the KEMAR manikin have been retained: e.g., the torso, the pinna that fits into the ear inserts, and the physical dimensions of the head.

The ear insert approximates the circumaural contours of the KEMAR head, and has an auditory canal that interfaces to the Zwislocki coupler and measurement microphone. The insert is covered with silicone rubber to simulate the mechanical properties of human circumaural and intraaural skin. In this phase of the study, the ALPHA was fitted on the ATF (see Figure 2) and measurements were carried out as described in the following three procedures.

A.1 *Investigation of ANR Attenuation Using Narrow-Band Noise*

The ATF was situated in a double-walled sound-proof booth (internal dimensions 2.9 x 3.2 x 2.3 meters) manufactured by the Industrial Acoustics Company (IAC). It was positioned 46 cm from the long wall, on the centre line facing into the room. The horizontal plane of the ATF ear canals was 1.6 meters above the floor. The narrow bands of noise described previously were reproduced by means of two Bose 802 speakers with 802E equalizers, orientated in the two longest dimensions of the room to produce a quasi random-incidence field around the head of the ATF.

SPLs were measured using the ½-inch pressure-response condenser microphone that forms the eardrum termination of the ATF ear-canal coupler. Measurements were made for two conditions: ANR *ON* and *OFF*. The difference between SPLs for the two conditions was considered the effectiveness (active attenuation) of the ANR system. The helmet was fitted onto the ATF head and the measurement carried out on three occasions to determine the effect of differences in helmet fit or placement on the measured attenuation. The resulting mean values and standard deviations are shown in Table 1.

A.2 *Investigation of ANR Attenuation Using Broadband Noise*

The attenuation of the ANR was evaluated in a quasi-reverberant room using the following broadband noises: (1) CH-124 Sea King helicopter noise, previously tape recorded in flight at the Sonar Observer's position [15] (see Table 2) and reproduced in the study using a tape loop, and (2) non-tonal broadband noise having the same general spectrum as the Sea King (see Figure 3).

The mean attenuation values of the ANR in the broadband noises, based on three fittings of the ALPHA on the ATF, are shown in Table 3 for the one-third octave measurement bands between 50 and 10,000 Hz. The effect of bandwidth (i.e., one-third versus one-twelfth octave) upon measured attenuation are given in Table 4. In this case, the

* The commercially available Knowles Electronics manikin for acoustic research (KEMAR), was developed by Burkhard and Sachs [12] primarily for hearing-aid research. The KEMAR was designed with medium human-adult dimensions of the torso, head and pinna, and cylindrical hard-wall canals approximating the length and diameter of the average human-adult auditory canal. A ½-inch pressure-response microphone terminates the ear canal via a Zwislocki coupler, which has four side branches to synthesize the acoustic impedance observed in human ears [13]

data were taken for the same fitting of the ALPHA on the ATF. During a subsequent fitting, measurements were taken simultaneously in the Sea King noise with (a) the ATF eardrum microphone, (b) the ANR sensing microphones, and (c) a probe microphone positioned at the entrance to the ear canal. The probe, a miniature ceramic microphone, was connected to an external amplifier by a thin ribbon cable in order that the seal between the ear muff cushion and the circumaural surface is not disturbed. The microphone and cable were secured to the external ear and neck with Micropore surgical tape so that the position of the microphone remained relatively fixed as the ear muff or helmet was donned and doffed. These results are shown in Table 5.

A.3 *Investigation of ANR System on Intercommunication Signals*

The response of the ANR system to intercom signals was determined to provide correction data for the *masking-procedure* phase of the study. Simply, the response was measured in the absence of external masking as the difference in KEMAR or ATF eardrum SPL * produced by pure tones on the intercom-signal input line with the ANR system *ON* and *OFF*. The tones were centred successively in each of the nine measurement bands previously specified. The resulting response curves are shown in Figure 4.

B. *Passive Attenuation Procedure*

In this study, male subjects were screened (1) for normal hearing (i.e., hearing threshold levels not greater than 10 dB at the test frequencies between 125 and 1000 Hz and not greater than 20 dB at the test frequencies between 2000 and 8000 Hz), and (2) for head sizes that permitted proper fitting of the ALPHA.

Each of six subjects was tested on two successive days as follows. The real-ear-at-threshold (REAT) attenuation ** of the ALPHA in the passive mode (ANR *OFF)* was determined at each of the one-third octave bands of noise centered at the nine standard test frequencies between 125 and 8000 Hz. This phase of the study was conducted to provide data on within- and between-subject variations in the attenuation of the helmet. A comparison was also made with previous ALPHA REAT data to determine the effect of the ANR components in the ear cup on the passive attenuation. The REAT results are given in Table 6.

C. *Masked Threshold Procedure*

One of the earliest descriptions of the use of a masking procedure to measure hearing protector attenuation was reported by Webster in 1955 [16]. An earphone was placed under the circumaural ear muff of a flight helmet worn by subjects in a noise field. The earphone delivered test tones to the subject so that his masked thresholds could be determined as a function of frequency when the helmet was worn and not worn. The change

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* In this instance, measurements were made using the KEMAR and ATF since responses were required for both the *right* and *left* earphones (the ATF has an instrumented ear canal only on the *left* side) to compare the effect of within-tolerance differences in components in the left and right ear-cup circuits. It was considered that the hard circumaural surface of the KEMAR, and hence the spring constant of the ear-muff cushion/head interface, would have no significant effect on the response measurements.

** The REAT procedure is the most common method of measuring the insertion loss of a passive hearing protector. Subjects' binaural diffuse-field hearing thresholds are measured in quiet with and without the hearing protector (occluded and unoccluded) using one-third octave bands of noise. A threshold shift is calculated, the difference in measured threshold between the two conditions providing a measure of the insertion loss of the protector. Because of its principle of operation, the active attenuation of an ANR system must be evaluated in a moderately intense noise environment. Obviously, the REAT procedure is not appropriate in this instance.

in masked threshold between the protected and unprotected conditions was considered to be the attenuation provided by the helmet. The results were found to agree within 5 dB with insertion-loss measures obtained for the helmet using the REAT procedure. However, the level of the noise in the one-third octave band centred about each test frequency had to be sufficiently intense to elevate the subject's unmasked threshold by at least the amount of attenuation expected from the test device.

After completion of the passive attenuation testing previously described, each subject was tested without doffing the ALPHA as follows. The subject was seated at the position occupied by the ATF in the IAC booth, and in the quasi-diffuse noise field described previously. The horizontal plane of the subjects' ear canals was about 1.4 meters above the floor. The narrow-band SPLs of the masking noise are listed in Table 7.

The ANR earphones in the flight helmet were used to deliver test tones to the subject's ears so that masked thresholds could be determined with the ANR system *ON* and *OFF*. They were driven from a low source impedance ($Z<0.1\Omega$) to minimize the effect of changes in load impedance on earphone output during the *OFF* and *ON* switching. Thresholds were determined using a Békésy tracking procedure. While the subject pressed his response button, the amplitude of the tone in the earphones decreased; while the button was released, the amplitude increased. In this manner, the subject tracked the signal between the thresholds of audibility and inaudibility and produced a time-history trace from which the masked thresholds were estimated [17]. The change in masked threshold between the two conditions, corrected to account for the pre-emphasis of intercom signals (i.e., the test tones) when the ANR is *ON*, was the measure of the effectiveness of the ANR system. The order of the two test masking conditions was randomized across subjects and replications. Subjects were not trained in this phase of the study since they had used the Békésy tracking procedure during their screening audiometry. The resulting means and standard deviations, pooled for the two days (D_{M1},D_{M2}), are given in Table 8.

D. *Loudness Balance Procedure*

Steeneken and Langhout [18] have used a loudness balance procedure to evaluate the Bose ANR noise-attenuating headset system. A subject was placed in a diffuse sound field which was changed once per second between two levels. Simultaneously, the ANR systems in the headset worn by the subject were switched *ON* during the more intense, and *OFF* during the less intense of the two diffuse-field periods (Figure 5). The subject was required to balance the levels for equal loudness by adjusting the level difference between the two diffuse-field sounds, the adjustment being made during the ANR *OFF-interval*. The resulting difference in sound level outside the ear muff was taken as the subjective attenuation provided by the ANR system.

In this phase of the study, the six subjects used in the previous procedures were tested as follows:

(1) Each subject underwent training on two successive days (D_{LB1},D_{LB2}) to practice the loudness-balance task. The test stimuli were bands of noise filtered to encompass the ERBs previously described. Before the start of each frequency loudness-balance, the subject was required to turn the *loudness* control fully anticlockwise (the least-loud end-point of the *OFF-interval* stimulus). Balance was achieved by adjusting the *OFF-interval* stimulus to be equally loud as the *ON-interval* stimulus, the *ON-interval* stimulus being held at a constant level. Subjects were instructed to ignore the click (mechanical switching noise of the ANR system), the slight change in stimulus timbre, and the ANR-system background noise that occurred each time the ANR system was cycled *ON* and *OFF*. The first practice day started with a practice loudness-balance at two

frequencies, followed by two trials (T_1,T_2) of loudness balancing at all nine frequencies. The second practice day D_{LB2} was identical except that the two initial-frequency loudness-balances were omitted.

(2) The two practice days were followed by two test days (D_{LB3},D_{LB4}), employing the same test protocol as in D_{LB2}.

The resulting mean values and standard deviations of attenuation, pooled for D_{LB3} and D_{LB4} (n=24), are shown in Table 9.

E. *Signal Detection Procedure*

The masked thresholds of three of the six subjects used in the masking and loudness-balance procedures were measured in the Sea King noise as previously described with the ANR *ON* and *OFF*. Five test frequencies were used (750, 1000, 1250, 1500 and 1750 Hz), encompassing the range of heterodyned frequencies employed to display active-sonobuoy and dipping-sonar returns. The difference in the masked-threshold tracings at a given frequency for the ANR *OFF* and *ON* conditions, corrected to exclude the effect of intercom-signal pre-emphasis, was taken as the improvement in signal detection performance due to ANR. The results are given in Table 10.

F. *Speech Intelligibility Procedure*

A common use of speech intelligibility testing to evaluate hearing protection involves the determination of the speech reception threshold (SRT) (the speech level at which 50 per cent correct identification of phonetically balanced or rhyming word lists occurs) of a listener with and without hearing protection. The difference in dB between the SRTs is then a measure of the protector's ability to reduce noise reaching the wearer's ears. The obvious limitation of the method is that the attenuation measure is not frequency specific. Nevertheless, the technique is important in estimating the communication effectiveness of personnel operating in noise environments with various types of protective equipment. Coles and Rice [19] and Forrest and Coles [20] used the procedure to ascertain the intelligibility of fire-control orders heard by military subjects wearing different types of ear plugs as a function of speaker-listener distance.

A less arduous method of measuring speech intelligibility, in terms of time required to test subjects, involves the use of artificial speech signals generated by the STIDAS II * speech-intelligibility measuring system. Forshaw *et al* [21] studied the speech-intelligibility and signal-detection characteristics of a combat-helmet sound-amplification system using this technique. Steeneken and Langout [18] used the STIDAS II system to evaluate the intelligibility characteristics of the Bose ANR system in noise.

In the STIDAS II procedure, the ALPHA was fitted on the ATF situated in a quasi random-incidence field. The STIDAS II test signal ** was connected to the ALPHA

* STIDAS II is a computer-based system developed at IZF-TNO, the Netherlands for the assessment of voice-communication system performance [22]. It consists of a digital modulator that produces artificial speech signals of given envelope spectrum, and an analysis section which measures the degradation of the modulation of the speech-signal envelope (modulation transfer function) in the octave bands between 125 and 8000 Hz, after the speech signal has been transmitted through the communication channel under test. The Transfer Index (TI) from each of the octave bands, weighted in proportion to the contribution of the band to the intelligibility of speech [23], is summed to give an overall index, defined as the Speech Transmission Index (STI) of the channel. The relationship between STI and speech intelligibility has been determined for phonetically balanced word lists using transmission-channel conditions involving noise and frequency bandpass limiting [22,24]. STI values may range from 0.0 to 1.0, indicating complete unintelligibility and complete intelligibility respectively.

** The STIDAS II signal is a random noise with a spectrum shape corresponding to that of average speech in the octave bands from 125 to 8000 Hz. The randomness of the signals is the source of the

intercom-input line and was calibrated to have equivalent speech levels of 70, 80, 90 and 100 dBA, measured at the ATF eardrum. At each SPL, the intelligibility (octave-band Transfer Indexes (TI) and overall Speech Transmission Indexes (STI)) were determined, based on five samples of the test signal, in quiet and in the Sea King noise. The resulting mean values and standard deviations are given in Table 2 The results are given in Tables 11 and 12.

RESULTS AND DISCUSSION

A. *ATF Measurements of ANR Effectiveness*

Comparison of the *t* values of the ANR attenuations for the Sea King with the broad-band spectra shown in Table 3 indicate significant differences ($p<.01$) in the mean values at 200, 1000 and 5000 Hz (5.0, 5.1 and 2.1 dB respectively). There are also significant differences between the narrow-band and broad-band noise attenuations at 63, 250, 630 and 1600 Hz (3.2, 2.1, 8.5 and 3.0 dB respectively (Tables 1 and 3)). It is not clear from the data whether these differences are due to interactions between ALPHA fit/refit variations, noise spectrum variations, and/or the amplitude and phase characteristics of the ANR feedback loop.

The fact that relatively large differences remain in one-third octave-band Sea King versus broad-band noise attenuations for the same ALPHA fitting (4.3 and 3.1 dB at 200 and 1000 Hz respectively (Table 4)) suggests that the major source of variance at these frequencies is the interaction of passband pressure levels and ANR *OFF/ON* response differences.

The pressure density level within a measurement passband may fluctuate considerably as a function of frequency. At the ATF eardrum with the ANR *OFF*, for example, these fluctuations are due to variations in the pressure field with frequency around the ATF head, the frequency-attenuation characteristics of the ALPHA, and the frequency response of the ear canal/Zwislocki coupler. When the ANR is *ON*, the fluctuations are due also to changes with frequency of the amplitude and phase characteristics of S_1S_2K in the ANR feedback loop (Figure 1).

In passbands where large changes in S_1S_2K occur, the separation in pressure response between the *OFF* and *ON* tracings also varies. When the measurement bandwidth is reduced from one-third to one-twelfth octave (Table 4), the respective between-spectra differences are reduced to 1.1 and 3.1 dB at 200 and 1000 Hz. One would expect that as the measurement bandwidth approaches 1 Hz, the observed ANR attenuation would become independent of noise-spectrum/ANR response interactions. In the present study this was not observed. Suffice it to say that at frequencies near which large changes occur in the feedback-gain characteristics of the ANR system, interactions between a noise spectrum and ANR *OFF/ON* response differences may result in measured attenuation differences that vary with spectrum and/or measurement bandwidth. As expected, the measured ANR attenuations vary considerably with the location of the measuring microphone (Table 5). Of interest, however, is whether the any of the measured attenuations agree with the psychophysical results reported in the following sections.

B. *Effect of ANR on ALPHA Passive Attenuation*

In the event that the ANR system becomes inoperative, wearers of the ALPHA are protected by the passive attenuation provided by the helmet. Since an ANR prototype circuit board is contained in each ear cup of the ALPHA used in this investigation, it is of interest to determine the effect of the resulting reduction in effective ear-cup volume

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replication variances observed in Tables 11 and 12.

on passive attenuation.

An analysis of Odell's passive-attenuation data for the ALPHA without ANR [25] (Appendix A (II)) and the present data (Table 6) indicates that the passive attenuation of the ALPHA with the prototype ANR is reduced by 12.5 dB at 500 Hz ($p<.001$) and increased by 5.3 dB at 1000 Hz ($p<.01$). At the other test frequencies, the differences are not significant ($p>.01$). In a production model, the effect of the ANR components on effective ear-cup volume and passive attenuation would be minimized by circuit miniaturization.

In comparing the two sets of ALPHA data, one observes that the standard deviations reported by Odell are considerably larger than those obtained in this study *. Both were carried out in the same test environment (i.e., the IAC sound-proof booth described previously) using the identical test procedure. In the present study, however, it was necessary to pay extraordinary attention to fitting the helmet on the subjects to prevent the low-frequency instability *howl* that resulted when the leakage between the ear-cup seal and the circumaural surface of the wearer's head became excessive. This instability problem is said to have been resolved in the most recent prototype ANR system [26].

C,D. *Psychoacoustic Measures of ANR Effectiveness*

The results of the masked-threshold (Table 8) and loudness-balance (Table 9) procedures (C and D) for evaluating the active attenuation of the ANR system show close agreement. These results, together with the objective measures obtained on the ATF (Table 1), are shown for comparative purposes in Figure 6.

Three principal questions arise from the results: (1) are the masked-threshold and loudness-balance procedures repeatable within themselves, (2) do the two procedures yield the same values of ANR active attenuation, and if so, (3) do they yield the same values of attenuation as the objective procedure?

1. The homogeneity of variance observed in the loudness-balance data was tested across *days* and *trials*. Although variance and active attenuation did not change significantly across *days* ($p>.01$), significant variability was found between *trials* across *days* in the 250-, 800- and 1000-Hz one-third octave bands. On the assumption that *learning* may have been a source of *between-trial* variance, the variance within *trials* was tested across *days*. No significant effect was found.

Variance across *days* within each *trial* is shown in Figures 7 to 9 for each frequency. Clearly, the variances are not homogeneous, and if consistency in response is a measure of task learning, there is no learning trend across days. To investigate the original design of the loudness-balance procedure (i.e., D_{LB1} and D_{LB2} were training days and D_{LB3} and D_{LB4} were test days), the variances were compared between $D_{LB1}+D_{LB2}$ and $D_{LB3}+D_{LB4}$. There was no significant differences between the two for either trial T_1 or T_2. Hence the data were pooled to give a sample size of n=24.

Homogeneity of variance could not be performed on the masked-threshold data, as only one repeat of the procedure was made. Accordingly, a repeated measures analysis of variance (ANOVA) [27] was used to look for a main effect across *days*. No significant difference was found. Hence the data were pooled to give a sample size of n=12.

2. To compare the values of active attenuation derived from the masked-threshold and the loudness-balance procedures, the following approach was used. As there was no apparent training effect over *days* or *trials* in the loudness-balance procedure, there was no rational way to use any particular combination of *days* or *trials*. Therefore,

* At 4000 Hz, the variance ratio is significant ($p<.01$).

comparisons were made using the repeated measures ANOVA of D_{M1} and D_{M2} against all loudness-balance *day/trial* combinations ($D_{LB1}T_1$, $D_{LB2}T_1$; $D_{LB1}T_2$, $D_{LB2}T_2$; $D_{LB3}T_1$, $D_{LB4}T_1$; and $D_{LB3}T_2$, $D_{LB4}T_2$). There was no significant difference between the two tests at any frequency. Moreover, there were no consistent trends across test frequency.

To investigate further the relationship between the two procedures, the results from the masked-threshold and loudness-balance procedures were correlated using three approaches:

(1) correlated over all subjects and frequencies, $0.851 \leq r \leq 0.876$ ($p < .001$), depending on which *trial/day* combination was used;

(2) correlated over all frequencies for each subject, $0.770 \leq r \leq 0.950$ ($p < .01$); and

(3) correlated over all subjects for each frequency (NC).

The inference from these results is that higher ANR attenuations are not obtained consistently within or between subjects across frequencies and procedures.

3. The results from the masking and loudness-balance procedures were compared separately against the ATF objective ERB data using *t-tests* for each frequency and each loudness-balance test-day combination (27 *t-tests* in all were performed). Significant differences in mean values of ANR attenuation were found as follows:

<u>630 Hz</u>
ERB versus $D_{LB1}+D_{LB2}$, p=.0003
ERB versus $D_{LB3}+D_{LB4}$, p=.0003
ERB versus $D_{M1}+D_{M2}$, p=.0001

<u>800 Hz</u>
ERB versus $D_{LB1}+D_{LB2}$, p=.003
ERB versus $D_{LB3}+D_{LB4}$, p=.003

<u>1600 Hz</u>
ERB versus $D_{M1}+D_{M2}$, p=.004

Using the conservative Bonferroni test of inequality [28], the acceptable probability level is $p \leq 0.002$. In this case, only the comparisons at 630 Hz are strictly significant statistically, although an examination of the data in Figure 5 would indicate significant differences at other frequencies (800 and 1600 Hz). It is not immediately clear whether these differences are attributable solely to differences between the objective and psychoacoustic measurement procedures, or additionally to differences in measurement bandwidths and/or differences between subjects' *real ears* and the ATF model ear.

The objective attenuation data (Table 1) were derived using the previously described ERBs, assumed to be equivalent to the bandwidths of the human peripheral auditory filter [11], and to be appropriate to the masking and loudness-balance tasks carried out by the test subjects. The ERB filter shape is based on a linear model of masking (i.e., masked thresholds correspond to constant signal-to-masker ratios at the output of the auditory filter), and applies to young listeners at moderate spectrum levels (40 to 60 dB).

To the extent that the assumptions on which the model is based are not entirely correct*, small differences in attenuation measures based on objective and psychoacoustic procedures may result. At the same time, one would expect that any gross bandwidth discrepancies between the ERB and the human auditory filter would be evident in the

* The bandwidth of the ERB tends to increase with age [29], and with sound level [30,31]. ERB bandwidths also vary somewhat among individuals.

masking and loudness-balance data over a relatively wide range of frequencies. Such was not the case in this study.

The results of previous measurements with the ATF [14] suggest that the physical and acoustical differences between the model ear and a *real ear* of the same dimensions probably did not contribute significantly to the differences observed in the objective and psychoacoustic measures of ANR attenuation. However, since the length and diameter of the ear canal have an effect on the eardrum sound pressure and on the electroacoustic amplitude and phase response of the ANR system, a more likely contribution probably originates from differences between the mean dimensions of the subjects' ear canals and those of the ATF ear canal. The ear canal of the ATF is slightly longer than the average human adult (22.7 mm rather than 21.5 mm).

Aside from these uncertainties, two questions remain to be addressed: (1) is one of the procedures more appropriate for the laboratory evaluation of ANR systems, and (2) what procedure might be appropriate for *in situ* evaluations? Of the two psychoacoustic tests, the loudness-balance procedure undoubtedly requires less time to complete and is easier for subjects to perform. Loudness balances are complicated at some frequencies, however, due to changes in the timbre of the noise between the ANR *OFF* and *ON* conditions.

Such changes of timbre do not affect the masked-threshold procedure. However, the task requires the continued attention of the subject, and, because it requires a longer time to complete, is more fatiguing. Further, if the subject's threshold is to be determined from a Békésy-type tracing, estimating the threshold may not be sufficiently precise without the use of automated data collection and scoring. However, the masked-threshold procedure lends itself to a criterion-free signal-detection paradigm (e.g., a two-alternative forced-choice procedure [32]), but requires an even longer time for completion. The latter may not be acceptable if the ANR evaluation is conducted in intense noise in which the required test durations pose a risk-to-hearing for subjects.

Objective evaluations using the ATF overcome the noise-exposure problem. Although differences may occur between objective and psychoacoustic measures of ANR attenuation at some frequencies, the ATF procedure may nevertheless be the most acceptable means of carrying out comparative evaluations between ANR systems with minimum expenditures of time and resources.

Because it is not normally possible to control conditions *in the field* for the satisfactory conduct of psychoacoustic experiments, neither the masked-threshold nor loudness-balance procedures lend themselves to ANR evaluations under operational conditions. A method commonly used involves the measurement of the difference in sound pressures inside the ear cup of a flight-helmet or headset, using a miniature (probe) microphone, when the ANR system is *OFF* and *ON*. Unless the microphone can be fixed at a common location, however, differences in the position of the transducer will result in extraneous pressure variations as shown in the results. The use of the ATF may lend itself to such measurements in the field. However, it must first be determined to what extent the ATF must be isolated from aircraft or vehicle vibration, and whether its compliant neck simulates sufficiently the response of the human neck and head to vibration as it affects the operation of a helmet- or headset-mounted ANR system. To summarize, the results of this study do not permit the recommendation of one procedure both for the laboratory and for *field* evaluation of ANR systems.

E. *Signal Detection Performance with ANR*

A comparison of the improvement in signal detection performance in Sea King noise (Table 10) with probe-microphone measures of attenuation due to ANR (Figure 10) indicates no direct relationship between performance improvement and increased signal-to-noise ratio (S/N). Whereas ANR attenuation (improved S/N) is generally greatest (>20

dB) between about 300 and 600 Hz, improvements in detection performance (>25 dB) extend up to at least 1000 Hz. This is due partly to a reduction in the upward spread of masking [33] by the intense energy in the low-order harmonics of the main-rotor noise of the aircraft.

The overall effect of ANR upon the noise exposure experienced by a Sea King Sonar Observer is illustrated in Figure 11. Octave-band and A-weighted SPLs are shown for three conditions in the CH-124 Sea King: (a) at the Sonar Observer's position during hover [15], (b) at the ear of a wearer of the flight helmet fitted with the prototype ANR, estimated from the mean values of passive attenuation of the helmet using the REAT procedure, and (c) at the ear of the wearer of the helmet, estimated from the active attenuation of the helmet (i.e., the passive attenuation plus the noise reduction provided by the ANR). The extent to which ANR enhances the low-frequency attenuation of the flight helmet is immediately evident. Mean attenuations at 63, 125, 250 and 500 Hz are increased by 11, 18, 26 and 13 dB respectively. With appropriate tuning of the ANR filter/amplifier, similar enhancements could be realized below 63 Hz. At the same time, it can be seen that ANR in its present configuration is not effective above 1000 Hz. At these frequencies, however, the flight helmet itself provides adequate noise attenuation.

To summarize, signal-detection performance may be used as a measure of the effectiveness of an ANR system in improving performance of the task. Because any improvement is not directly related to noise reduction *per se*, however, the measure is specific to the detection task and the masking spectrum in which it is performed.

F. *Speech Intelligibility Measures of ANR Effectiveness*

The speech intelligibility characteristics of the ALPHA/ANR are influenced by the electroacoustic sensitivity S_1 of the earphone and the acoustical characteristics K of the enclosed volume under the ear cup (Figure 1), including the transfer characteristics of the ear canal. Superimposed on these when the ANR is *ON* are the frequency-response characteristics of the phase-compensation filter and drive amplifier (G_1 and G_2), the electroacoustic sensitivity of the sensing microphone S_2, and the intercom-signal pre-emphasis (Figure 4).

The effect of these factors on the ANR earphone output is shown in Table 11. The output, measured at the ATF eardrum with a constant-amplitude signal at the intercom-input line, is shown for ANR *OFF* and *ON* conditions. In the *OFF* condition, the response of the earphone/enclosed volume has a low-frequency peak (+15 dB) relative to the 1000-Hz baseline, and a sharp notch (-12 dB) at 4000 Hz. In the *ON* condition, the low-frequency peak disappears and the high-frequency notch deepens (-21 dB).

The intelligibility characteristics of the system, measured using STIDAS II in the absence of masking noise, are given in Table 12 in terms of octave-band TIs and overall STI. It can be seen that the ANR system does not appear to overload * over the 30 dB input-signal amplitude range studied, and that the ANR system reduces the intercom signal at the eardrum by about 8 dBC (5 dBA).

Of interest, however, is the small reduction in STI when the ANR is *ON*. This is not due to harmonic distortion, as was confirmed using the STIDAS II in an alternative measuring mode. Rather, the reason can be seen in the upper graphs in Figures 12 to 15. In the *OFF* condition, a relatively small TI value occurs in the 4000-Hz octave band due to the notch at that frequency in the earphone response (Table 11). In the *ON* condition, the TIs at 4000 and 8000 Hz are reduced further, reflecting the more extensive fall-off in system high-frequency response with the ANR *ON*.

* Incremental changes in intercom-signal input level produce the same incremental changes in eardrum SPL

The noise-reduction and speech-intelligibility characteristics of the system in Sea King noise are given in Table 13. At signal levels between 90 and 100 dBA, the ANR reduces the signal and noise at the eardrum by about 9 dBC (5 dBA), and increases the C- and A-weighted signal-to-noise ratios (S/N) by 7 and 8 to 9 dB respectively. It is also clear that when intercom equivalent signal levels fall below 90 dBA in this noise, STIs remain below 0.30 and intelligibility is unacceptable *.

The effect of the Sea King noise on octave-band TIs is shown in the lower graphs of Figures 12 to 15. At 70 JBA signal level (Figure 12), the poor S/Ns result in very small TIs. When the signal is at 80 and 90 dBA, the effectiveness of ANR in the frequency range 200 to 600 Hz becomes evident in the differences in TI in the ANR *OFF* and *ON* conditions (Figures 13 and 14). The ineffectiveness of ANR at 2000 Hz (the octave-band contributing most to intelligibility) is also evident, and at signal levels below 90 dBA, precludes much improvement in overall STI (.359 to .457 at 90 dBA). At 100 dBA, the improvement in STI due to ANR is less dramatic (.654 to .699). The very intense signal yields relatively high values of S/N and TI in the 250, 500 and 1000 Hz octave bands, even in the ANR *OFF* condition (Figure 15). In the *ON* condition, additional improvement is limited by further *headroom* in these bands and by the poor performance of the ANR in the higher octave bands.

To summarize, a measure of speech intelligibility may be used to assess the effect on communications of an ANR system. Because overall intelligibility is governed by system parameters (e.g., bandwidth, spectrum enhancement, dynamic range) and the acoustic environment of the listener, the measure is specific to the system and environment in which the evaluation was conducted.

CONCLUSIONS

1. When the attenuation of an ANR system is measured objectively with a transducer inside the earmuff/ear-canal volume, the location of the transducer affects the observed ANR attenuations.

2. At frequencies where large changes occur in the feedback-gain characteristics of the ANR system, interactions between a noise spectrum and ANR *OFF/ON* response differences may result in differences in objective attenuation measures that vary with spectrum and/or measurement bandwidth.

3. The mid-frequency passive attenuation of the ALPHA was found to be reduced significantly with the addition of the prototype ANR components inside the ear cups. In a production model, the effect of the components on effective ear-cup volume and passive attenuation could be minimized by circuit miniaturization.

4. Refinements to the psychoacoustic procedures require investigation. Objective measures of ANR performance have the potential for useful field and laboratory investigations. However, the head-vibration characteristics of the ATF need to be addressed if this technique is to be implemented *in the field.*

5. The results of this study do not clearly permit the recommendation of one procedure for the laboratory and *field* evaluation of ANR systems.

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* Based on the third-order polynomial relationship of Steenekin and Agterhuis [34], STI values of 0.3, 0.5 and 0.7 are equivalent to intelligibility scores of 35, 73 and 95 per cent respectively for phonetically-balanced monosyllabic word lists. With the negative exponential relationship of Raymond [24], the same values of STI are equivalent to intelligibility scores of 55, 78, and 91 per cent respectively.

6. Signal-detection performance may be used as a measure of the effectiveness of an ANR system in improving performance on this task. Because the amount of improvement, if any, is not directly related to noise reduction *per se*, the measure is specific to the detection task and the masking spectrum in which it is performed.

7. A measure of speech intelligibility may be used to assess the effect on communications of an ANR system. Because overall intelligibility is governed by system parameters (e.g., bandwidth, spectrum enhancement, dynamic range) and the acoustic environment of the listener, the measure is specific to the system and environment in which the evaluation was conducted.

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TABLE 1

ACTIVE ATTENUATION (dB) OF ANR SYSTEM MEASURED IN NARROW-BAND NOISE ON THE ATF

	Equivalent Rectangular-Bandwidth Centre Frequency in Hz								
	63	125	250	315	500	630	800	1000	1600
Mean ($\bar{x}$)(n=3)	3.6	14.3	19.7	24.5	22.7	7.7	-0.7	-2.7	-7.3
S.D. (σ)	0.8	0.7	0.3	1.2	2.8	1.3	2.6	1.7	1.0

TABLE 2

DIFFUSE-FIELD SEA KING HELICOPTER NOISE‡

Octave-Band Centre Frequency in Hz	Sound Pressure Level	
	Reproduced	Actual (Sonar Observer) (After Forshaw and Stong, 1972)
31.5	81 dB	96 dB
63	96 dB	96 dB
125	95 dB	97 dB
250	98 dB	95 dB
500	96 dB	95 dB
1000	87 dB	84 dB
2000	82 dB	81 dB
4000	80 dB	79 dB
8000	76 dB	91 dB

‡ Flight Conditions: Hover at 40 ft., Torque = 68 per cent.

TABLE 3

ONE-THIRD OCTAVE BAND ACTIVE ATTENUATION (dB) OF ANR SYSTEM MEASURED ON ATF IN SEA KING AND BROAD-BAND NOISE (n=3)

	Sea King Noise		*Broad-Band Noise*	
Frequency (Hz)	$\bar{x}$	σ	$\bar{x}$	σ
50	4.1	1.5	3.6	1.2
63	5.8	0.6	6.8	0.2
80	9.4	0.9	10.2	0.1
100	12.2	0.2	13.1	0.4
125	15.4	0.1	15.1	0.3
160	18.3	0.4	16.8	0.6
200	19.0	1.3	14.0	1.0
250	20.6	0.8	17.4	1.3
315	23.1	0.6	19.7	2.6
400	25.4	3.4	23.1	2.8
500	17.4	2.5	19.5	1.2
630	14.0	1.8	16.2	0.9
800	1.3	3.0	1.8	0.5
1000	-10.8	0.7	-5.7	1.3
1250	-4.9	1.4	-3.1	0.9
1600	-1.2	1.2	-1.0	0.5
2000	-2.6	0.4	-2.9	0.5

TABLE 4

ACTIVE ATTENUATION (dB) OF ANR SYSTEM DETERMINED IN SEA KING AND BROAD-BAND NOISE ON ATF, AS A FUNCTION OF MEASUREMENT BANDWIDTH

	One-Third Octave		*One-Twelfth Octave*	
Frequency (Hz)	Sea King	Broad Band	Sea King	Broad Band
125	15.5	15.4	15.3	15.1
160	17.9	17.3	17.5	16.6
200	18.2	13.9	17.9	16.8
250	19.6	17.9	19.3	18.5
315	23.9	22.0	26.0	22.6
400	26.5	22.8	26.6	23.5
500	19.5	19.6	19.4	18.3
630	16.1	16.0	13.0	13.6
800	1.9	0.5	-1.5	-0.5
1000	-8.9	-5.8	-9.7	-7.2
1250	-4.7	-3.5	-1.1	-1.2
1600	-0.3	-0.4	-0.3	-2.5
2000	-3.1	-2.4	-3.6	-2.1

TABLE 5

ACTIVE ATTENUATION (dB) OF ANR SYSTEM MEASURED ON ATF AT FOUR LOCATIONS

	One-Third Octave-Band Centre Frequency in Hz								
	63	125	250	315	500	630	800	1000	1600
Eardrum Microphone	6.0	15.7	20.1	19.8	20.7	18.1	3.5	-6.7	-2.8
Probe Microphone[a]	5.1	14.2	17.4	18.4	19.9	19.0	13.2	-5.3	-3.9
Probe Microphone[b]	7.4	15.9	11.9	6.2	19.5	21.9	17.4	4.3	-2.5
ANR Sensing Microphone	6.2	15.8	22.1	24.4	18.3	15.8	13.0	1.8	-11.9

(a) Probe microphone was a Knowles BL1785 ceramic microphone taped to the ATF antritragus with surgical tape. The plane of the microphone diaphragm was horizontal, positioned at the entrance to the ear canal in the center of the concha volume (midconcha).

(b) As in (a), but the diaphragm of the microphone approximately 0.2 cm below the midconcha.

TABLE 6

PASSIVE ATTENUATION (dB) OF ALPHA FITTED WITH ANR SYSTEM

	One-Third Octave-Band Centre Frequency in Hz								
	125	250	500	1000	2000	3150	4000	6300	8000
Mean ($\bar{x}$)(n=12)	12.5	12.3	12.0	33.7	32.6	41.3	48.5	44.8	44.3
S.D. (σ)	2.4	2.4	2.5	3.0	4.0	4.5	3.2	4.8	5.0

TABLE 7

DIFFUSE-FIELD NARROW-BAND NOISE LEVELS OF MASKER

One-Third Octave-Band Centre Frequency in Hz	Sound Pressure Level (dB)
63‡	100 dB
125	93 dB
250	95 dB
315	98 dB
500	89 dB
630	93 dB
800	99 dB
1000	101 dB
1600	94 dB

‡ Full octave bandwidth.

TABLE 8

ACTIVE ATTENUATION (dB) OF ANR SYSTEM
USING THE MASKED-THRESHOLD PROCEDURE

	One-Third Octave-Band Centre Frequency in Hz								
	63‡	125	250	315	500	630	800	1000	1600
Mean ($\bar{x}$)(n=12)	5.2	11.9	19.4	23.9	26.1	19.8	8.4	-1.0	-3.7
S.D. (σ)	2.3	3.6	3.0	2.4	3.2	2.3	5.4	6.2	1.5

‡ Full octave bandwidth.

TABLE 9

ACTIVE ATTENUATION (dB) OF ANR SYSTEM
USING THE LOUDNESS-BALANCE PROCEDURE

	One-Third Octave-Band Centre Frequency in Hz								
	63‡	125	250	315	500	630	800	1000	1600
Mean ($\bar{x}$)(n=24)	3.8	12.4	18.1	21.6	25.3	21.2	9.5	3.6	-1.0
S.D. (σ)	2.9	4.0	2.7	2.8	4.0	4.0	3.9	4.4	4.3

‡ Full octave bandwidth.

TABLE 10

IMPROVEMENT IN SIGNAL DETECTION (dB)
IN SEA KING NOISE WITH ANR‡

	Test-Tone Frequency (Hz)				
	750	1000	1250	1500	1750
Mean ($\bar{x}$)(n=3)	26.3	25.0	17.3	6.7	0.3
S.D. (σ)	1.0	1.0	1.5	2.1	2.1

‡ Excluding the effect of intercom-signal pre-emphasis.

TABLE 11

RELATIVE OUTPUT OF ANR EARPHONE FOR CONSTANT SIGNAL AMPLITUDE
AT THE INTERCOM-INPUT LINE, MEASURED AT THE ATF EARDRUM

Frequency (Hz)	Response (dB)	
	ANR OFF‡	ANR ON*
63	+10.2	+0.6
125	+10.6	-1.9
250	+15.4	-2.9
500	+11.1	-2.8
630	+9.4	-2.6
800	+4.0	-1.7
1000	0.0	0.0
1250	-5.0	+1.8
1600	-4.6	+2.6
2000	-0.9	-2.1
2500	-1.6	-5.7
3150	-10.1	-14.2
4000	-12.1	-21.5
5000	0.6	-13.0
6300	3.8	-6.1
8000	4.6	-11.8

‡ Baseline: 90 dB SPL at 1000 Hz.
* Baseline: 98 dB SPL at 1000 Hz.

TABLE 12

OVERALL AND OCTAVE-BAND SPL, TI AND STI OF STIDAS SIGNAL MEASURED AT THE ATF EARDRUM IN QUIET

Octave-Band Centre Frequency (Hz)	*ANR OFF*		*ANR ON*	
	SPL	*TI*	*SPL*	*TI*
STIDAS SIGNAL = 70 dBA				
125	68.3 dB	.93	61.9 dB	.93
250	75.1 dB	.97	64.1 dB	.94
500	71.2 dB	.95	63.4 dB	.98
1000	56.3 dB	.91	62.8 dB	.97
2000	47.9 dB	.98	55.1 dB	.95
4000	41.5 dB	.67	41.0 dB	.42
8000	43.7 dB	.84	42.1 dB	.37
	77 dBC		69 dBC	
	71 dBA		66 dBA	
STI $\bar{x}$ (n=5)		.886		.777
STI σ		.028		.027
STIDAS SIGNAL = 80 dBA				
125	78.4 dB	.96	72.3 dB	.97
250	85.0 dB	.97	74.3 dB	.96
500	81.1 dB	.95	73.5 dB	.99
1000	66.1 dB	.89	73.5 dB	.98
2000	56.7 dB	.98	65.4 dB	.95
4000	47.6 dB	.73	44.4 dB	.49
8000	50.7 dB	.86	45.3 dB	.70
	87 dBC		80 dBC	
	81 dBA		76 dBA	
STI $\bar{x}$ (n=5)		.916		.847
STI σ		.011		.018
STIDAS SIGNAL = 90 dBA				
125	88.4 dB	.94	82.0 dB	.97
250	95.2 dB	.95	84.2 dB	.96
500	91.0 dB	.92	83.1 dB	.97
1000	76.0 dB	.91	82.9 dB	.99
2000	66.4 dB	.98	74.7 dB	.97
4000	57.0 dB	.72	52.5 dB	.40
8000	60.0 dB	.95	52.7 dB	.89
	97 dBC		89 dBC	
	91 dBA		86 dBA	
STI $\bar{x}$ (n=5)		.907		.862
STI σ		.007		.013

TABLE 12 CONTINUED

Octave-Band Centre Frequency (Hz)	*ANR OFF* SPL	TI	*ANR ON* SPL	TI
STIDAS SIGNAL = 100 dBA				
125	98.0 dB	.64	91.3 dB	.95
250	105.0 dB	.99	94.1 dB	.99
500	101.0 dB	.99	93.1 dB	.99
1000	85.5 dB	.91	92.9 dB	.97
2000	76.2 dB	.97	84.4 dB	.97
4000	66.6 dB	.75	62.3 dB	.42
8000	69.7 dB	.97	62.1 dB	.95
	107 dBC		99 dBC	
	100 dBA		96 dBA	
STI $\bar{x}$ (n=5)		.924		.876
STI σ		.010		.011

TABLE 13

OVERALL AND OCTAVE-BAND SPL, TI AND STI OF STIDAS SIGNAL IN SEA KING NOISE MEASURED AT THE ATF EARDRUM

Octave-Band Centre Frequency (Hz)	*ANR OFF* SPL	S/N	TI	*ANR ON* SPL	S/N	TI
STIDAS SIGNAL = 70 dBA						
125	79.9 dB	-11.1	.16	66.3 dB	-2.5	16
250	84.1 dB	-9.2	.10	67.1 dB	-0.1	17
500	80.8 dB	-9.3	.09	65.8 dB	0.9	19
1000	57.8 dB	3.3	.04	64.2 dB	4.6	12
2000	51.4 dB	-1.7	.02	56.4 dB	3.1	02
4000	48.1 dB	-6.7	.02	48.7 dB	-7.9	05
8000	43.4 dB	3.1	.00	42.0 dB	0.2	01
	87 dBC			72 dBC		
	80 dBA			68 dBA		
STI $\bar{x}$ (n=5)			055			095
STI σ			008			013

TABLE 13 CONTINUED

Octave-Band Centre Frequency (Hz)	*ANR OFF*			*ANR ON*		
	SPL	*S/N*	*TI*	*SPL*	*S/N*	*TI*
STIDAS SIGNAL = 80 dBA						
125	82.0 dB	-1.1	.22	72.9 dB	8.0	.19
250	87.8 dB	0.8	.27	74.7 dB	10.6	.58
500	83.8 dB	1.0	.22	74.0 dB	11.7	.57
1000	66.5 dB	13.8	.33	73.2 dB	15.1	.36
2000	57.5 dB	6.8	.05	65.1 dB	13.7	.15
4000	50.1 dB	0.4	.01	48.8 dB	-3.1	.05
8000	50.3 dB	9.6	.19	45.2 dB	3.0	.00
	90 dBC			80 dBC		
	83 dBA			76 dBA		
STI $\bar{x}$ (n=5)			.169			.251
STI σ			.015			.009
STIDAS SIGNAL = 90 dBA						
125	88.8 dB	7.9	.17	81.6 dB	16.7	.30
250	95.4 dB	11.7	.58	84.2 dB	21.1	.91
500	91.2 dB	9.6	.53	83.1 dB	19.8	.88
1000	75.9 dB	21.9	.62	82.8 dB	23.7	.69
2000	66.4 dB	16.1	.22	74.5 dB	22.4	.42
4000	57.6 dB	10.2	.03	53.5 dB	4.3	.03
8000	59.8 dB	19.3	.55	52.5 dB	10.5	.18
	98 dBC			89 dBC		
	91 dBA			86 dBA		
STI $\bar{x}$ (n=5)			.359			.457
STI σ			.013			.011
STIDAS SIGNAL = 100 dBA						
125	98.3 dB	17.3	.39	91.8 dB	26.0	.67
250	105.3 dB	21.4	.93	94.1 dB	30.9	.97
500	101.0 dB	20.3	.85	93.0 dB	29.5	.97
1000	85.8 dB	31.7	.86	92.8 dB	33.4	.94
2000	76.0 dB	25.7	.56	84.6 dB	31.7	.74
4000	67.0 dB	19.4	.29	62.4 dB	14.3	.08
8000	69.5 dB	29.1	.85	62.5 dB	20.4	.54
	107 dBC			99 dBC		
	101 dBA			96 dBA		
STI $\bar{x}$ (n=5)			.654			.669
STI σ			.011			.006

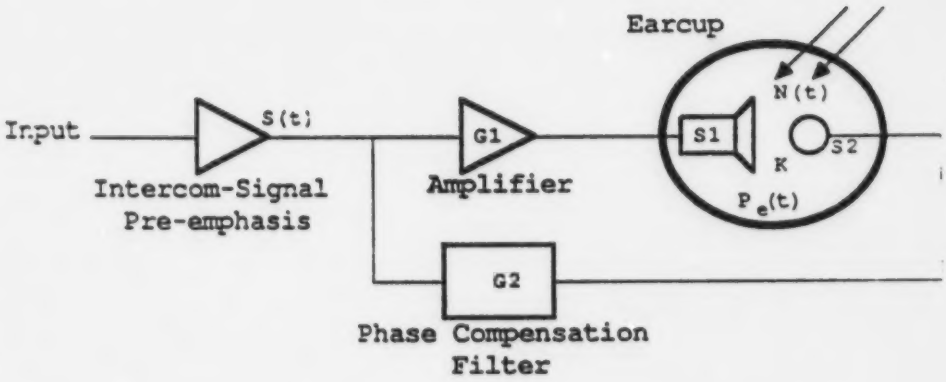

FIGURE 1. Block diagram of the ANR system (after Wheeler and Halliday (1981)).

FIGURE 2. The Helmets Limited (UK) Advanced Lightweight Protective Helmet for Aircrew (ALPHA) fitted on the acoustic test fixture (ATF).

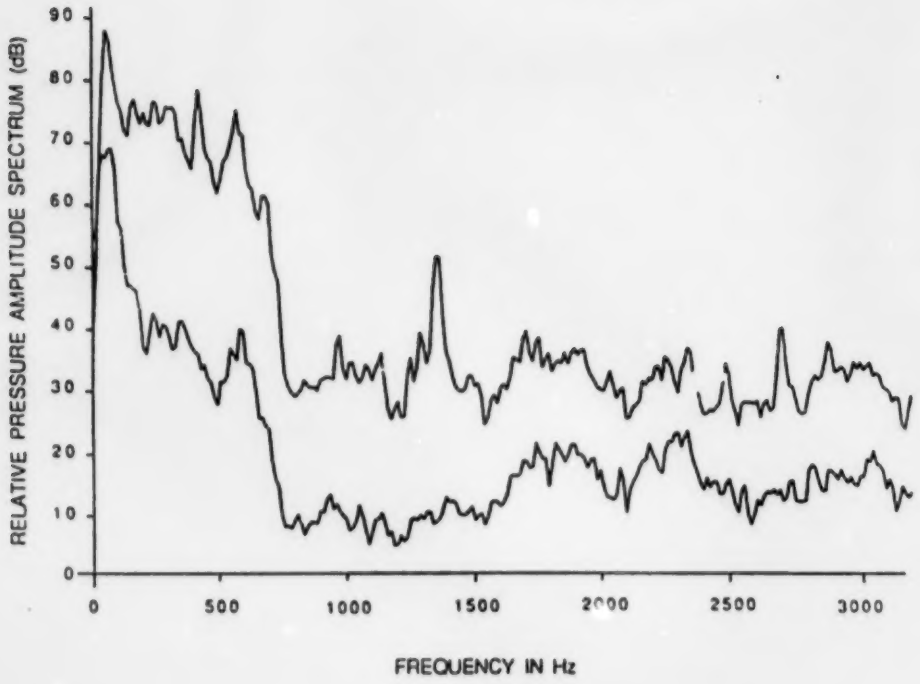

FIGURE 3. Relative pressure amplitude spectrum levels in dB of the Sea King helicopter (upper tracing) and broadband noise (lower tracing) under the ALPHA/ANR (ANR *OFF)* mounted on the ATF, measured at the ATF ear drum. Note that the upper and lower tracings are separated vertically to facilitate comparison, although the overall levels are the same.

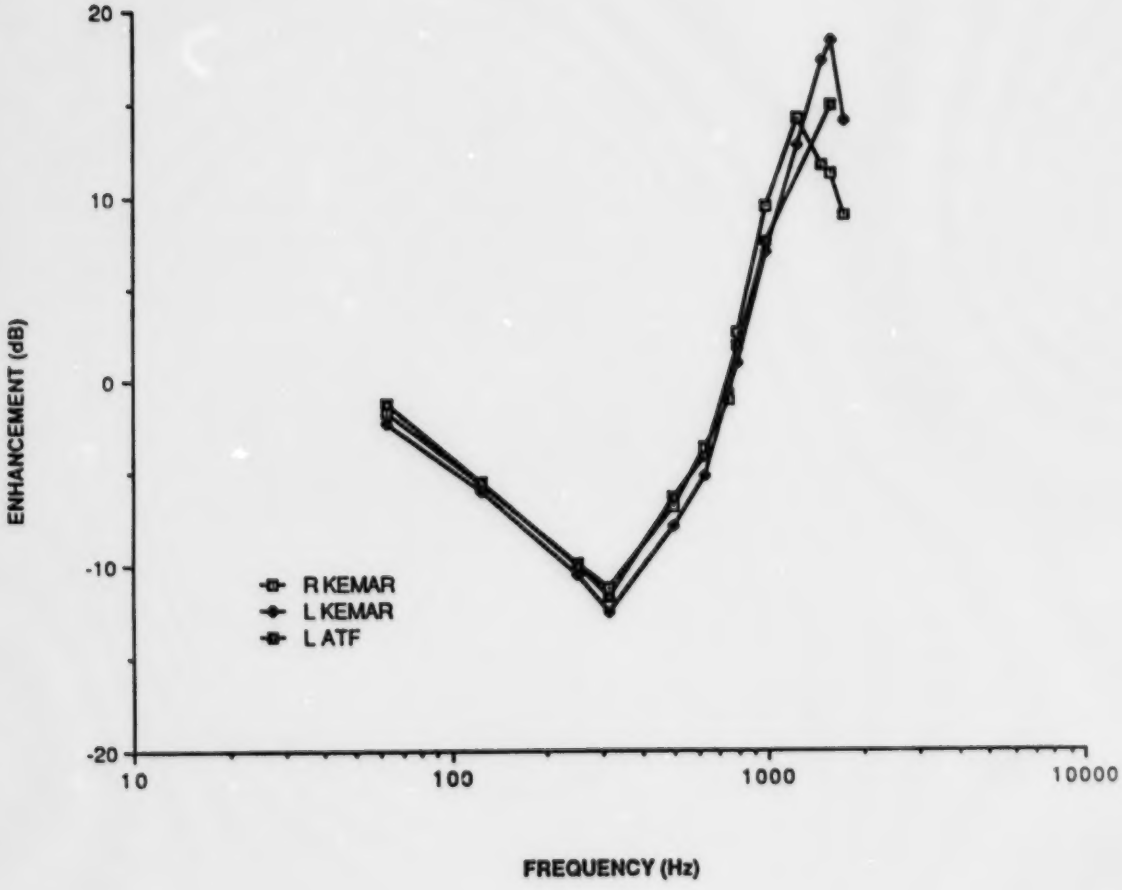

FIGURE 4. Response of ANR system (Left ear on the KEMAR and ATF, Right ear on the KEMAR) to intercom signals.

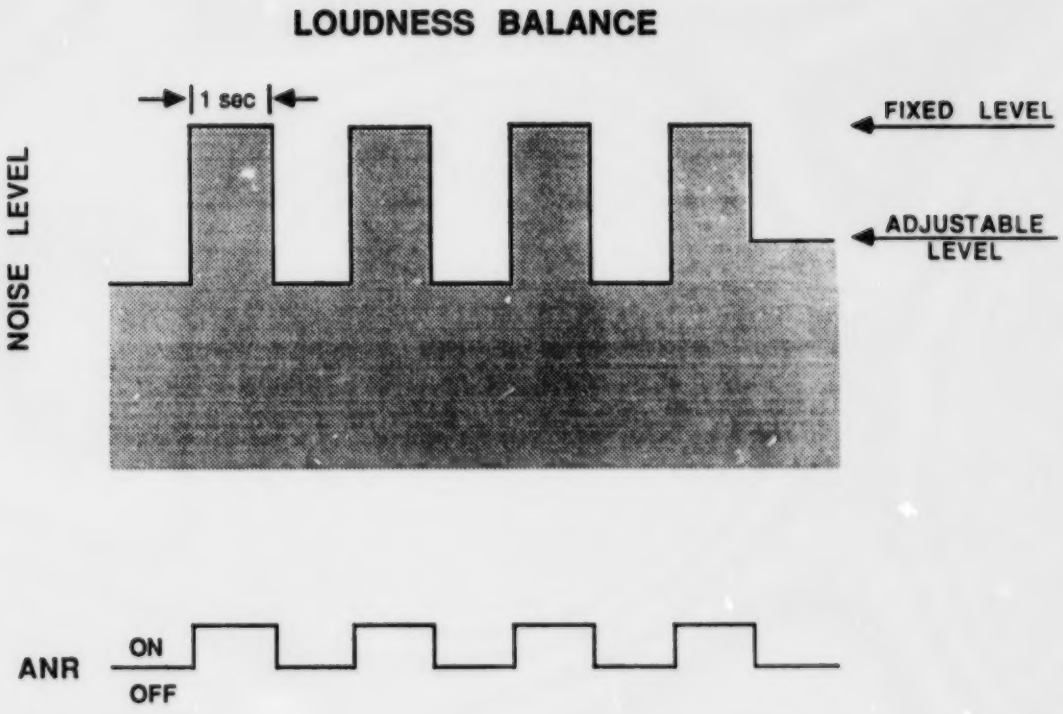

FIGURE 5. Time relationship between ANR *ON/OFF* conditions and changes in diffuse-field noise levels. Loudness balance between the two ANR conditions is achieved by adjusting the level of the noise during the *OFF* condition.

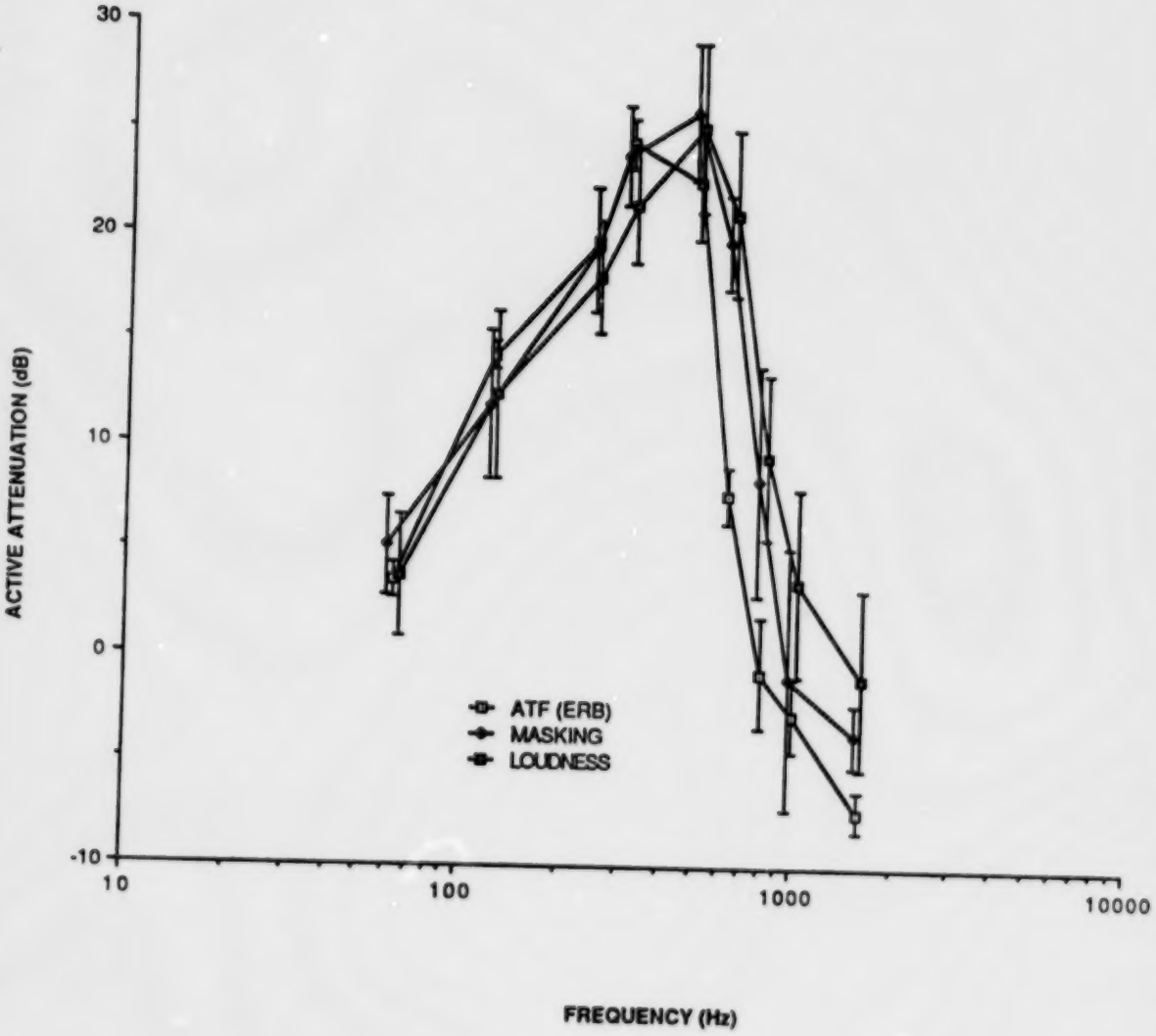

FIGURE 6. Active attenuation of ANR system as determined by (a) ear-canal measurements on the acoustic test fixture (ATF) with equivalent rectangular bands of noise (ERB), (b) the masking threshold-shift procedure, and (c) the loudness-balance procedure. The vertical bars represent one standard deviation above and below the mean. The datum points are offset slightly along the frequency axis to facilitate comparison of the standard deviations of the three curves.

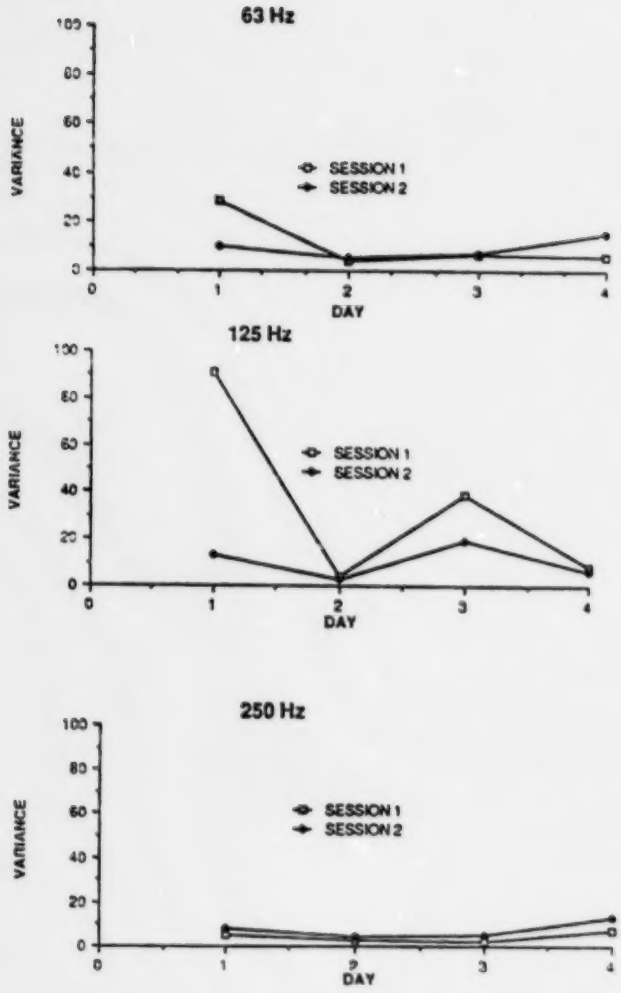

FIGURE 7. Loudness-balance within *trials* at 63, 125 and 250 Hz, across subjects as a function of *day*.

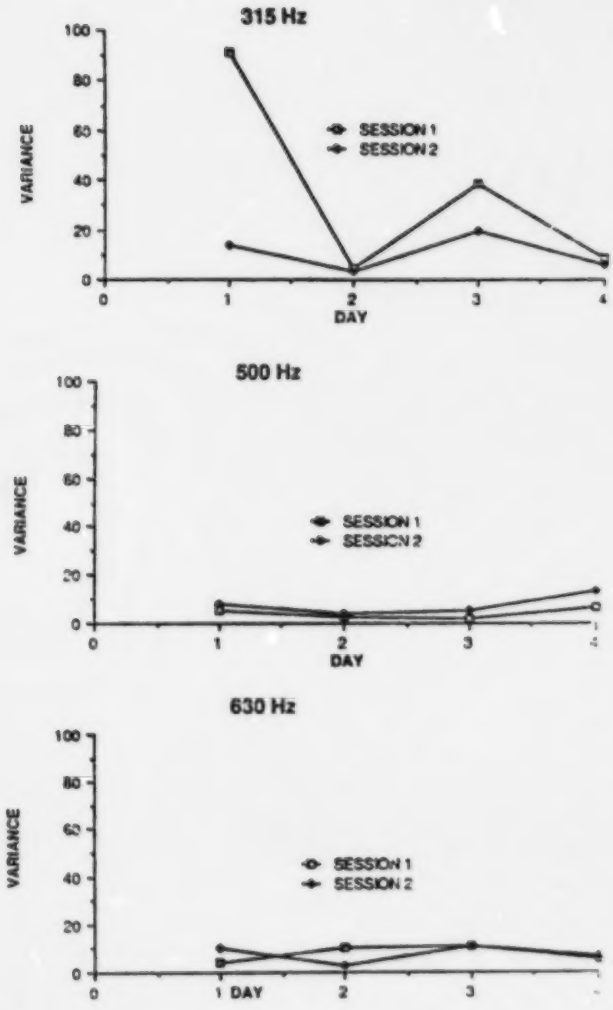

FIGURE 8. Loudness-balance within *trials* at 315, 500 and 630 Hz, across subjects as a function of *day*.

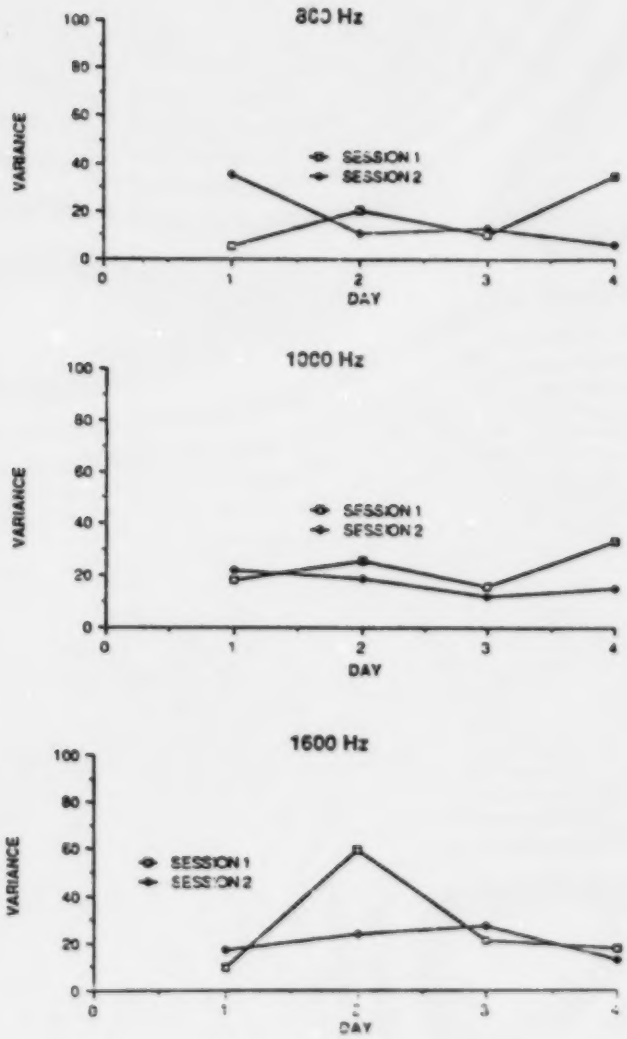

FIGURE 9. Loudness-balance within *trials* at 800, 1000 and 1600 Hz, across subjects as a function of *day*.

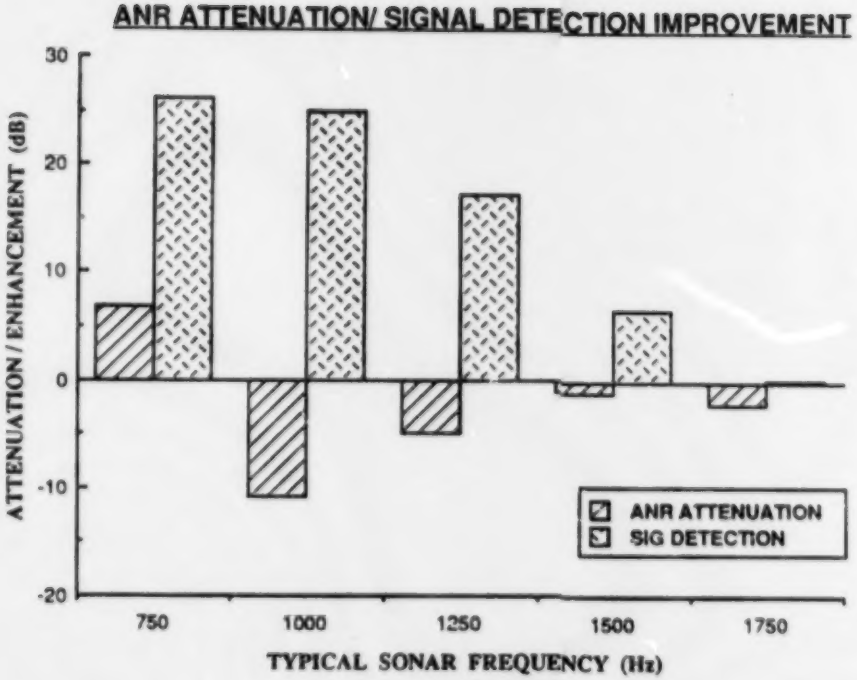

FIGURE 10. Improvement in signal detection performance and signal-to-noise ratio under the ALPHA, in recorded Sea King noise due to ANR, at 750, 1000, 1250, 1500 and 1750 Hz.

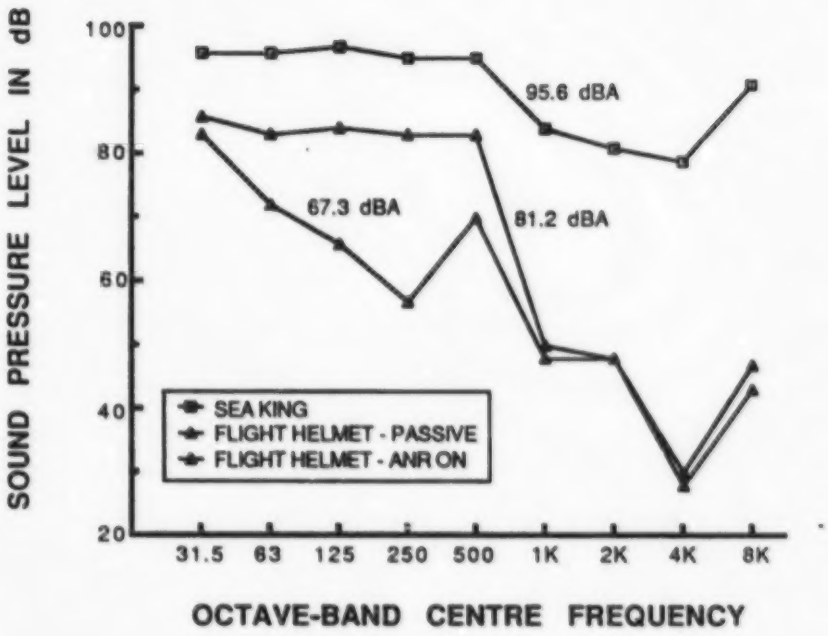

FIGURE 11. Octave-band and A-weighted overall sound pressure levels: (a) in the Sea King helicopter at the Sonar Observer's position during hover (Forshaw and Stong, 1972),(b) at the ear of a wearer of the flight helmet with ANR system *OFF*, estimated from the mean values of attenuation of the helmet, and (c) at the ear of the wearer of the ALPHA with ANR system *ON*.

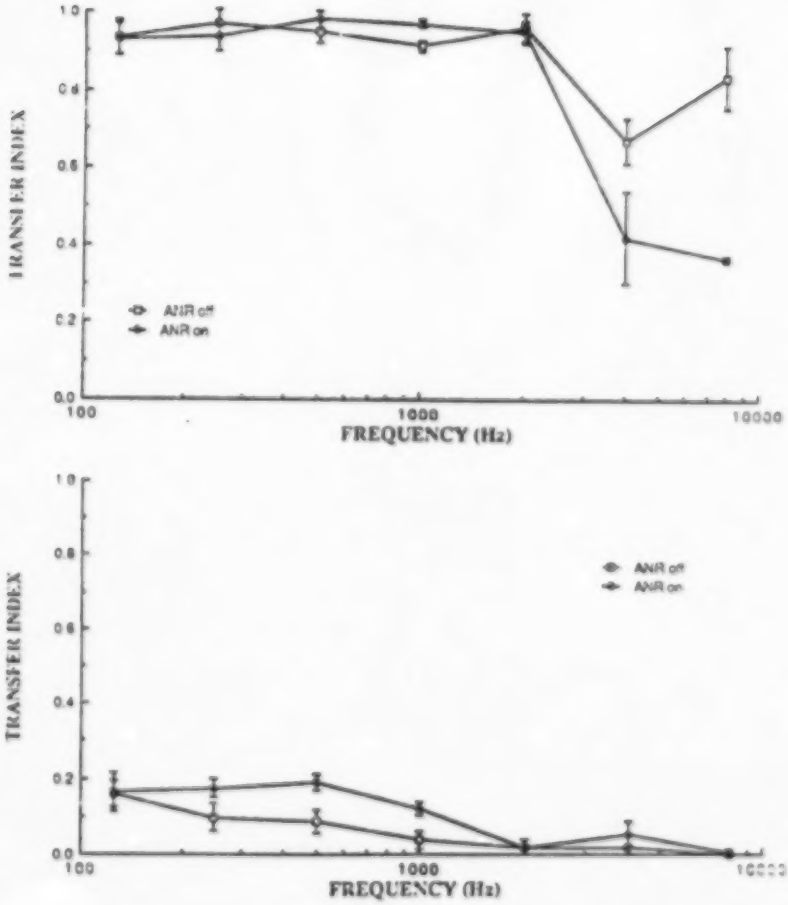

FIGURE 12. Octave-band Transmission Indexes (TI) of ANR in quiet (upper graph) and Sea King noise (lower graph), ANR *OFF* and *ON*, for an intercom signal level of 70 dBA measured at the ATF eardrum. The vertical bars represent one standard deviation above and below the mean.

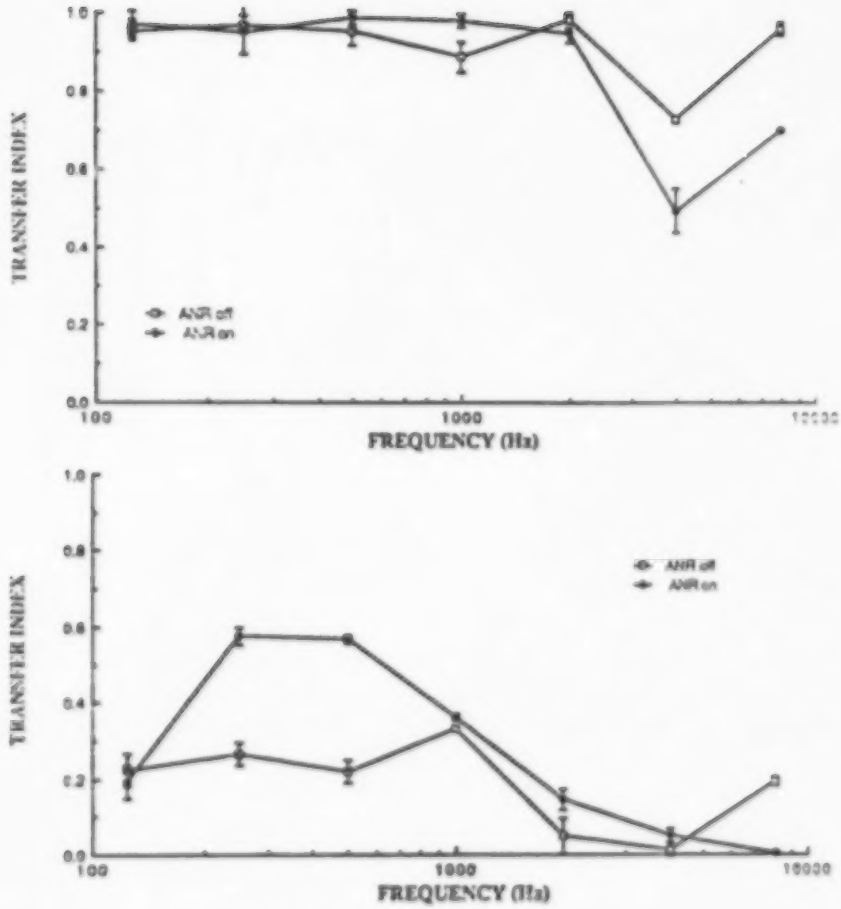

FIGURE 13. Octave-band Transmission Indexes (TI) of ANR in quiet (upper graph) and Sea King noise (lower graph), ANR *OFF* and *ON*, for an intercom signal level of 80 dBA measured at the ATF eardrum. The vertical bars represent one standard deviation above and below the mean.

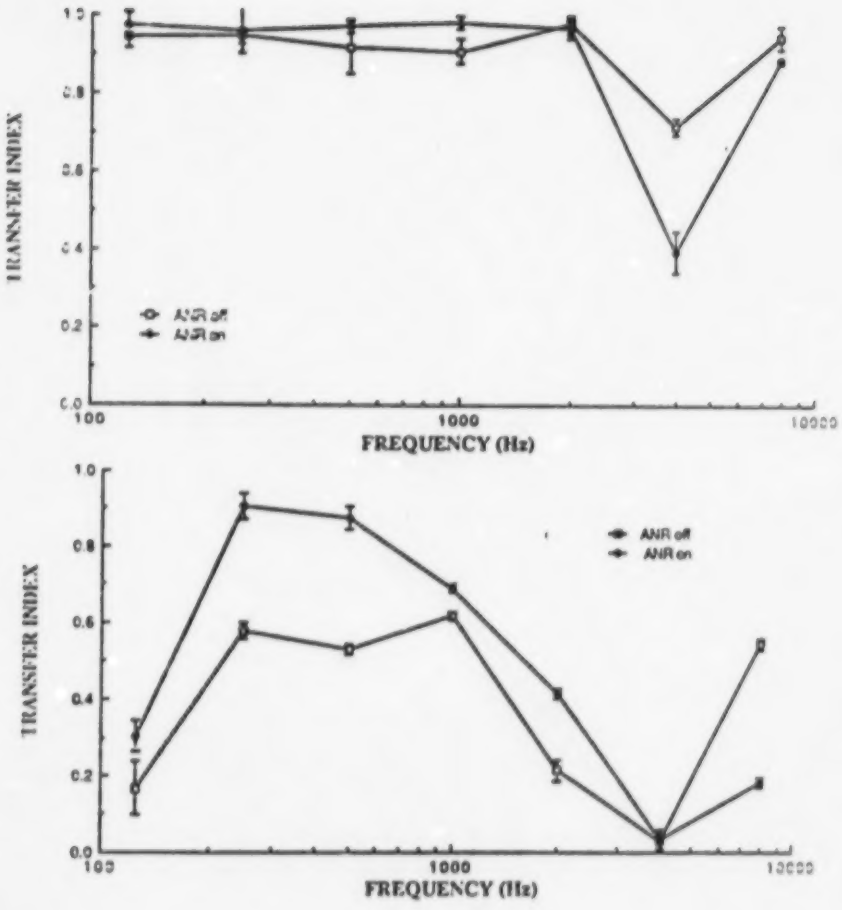

FIGURE 14. Octave-band Transmission Indexes (TI) of ANR in quiet (upper graph) and Sea King noise (lower graph), ANR *OFF* and *ON*, for an intercom signal level of 90 dBA measured at the ATF eardrum. The vertical bars represent one standard deviation above and below the mean.

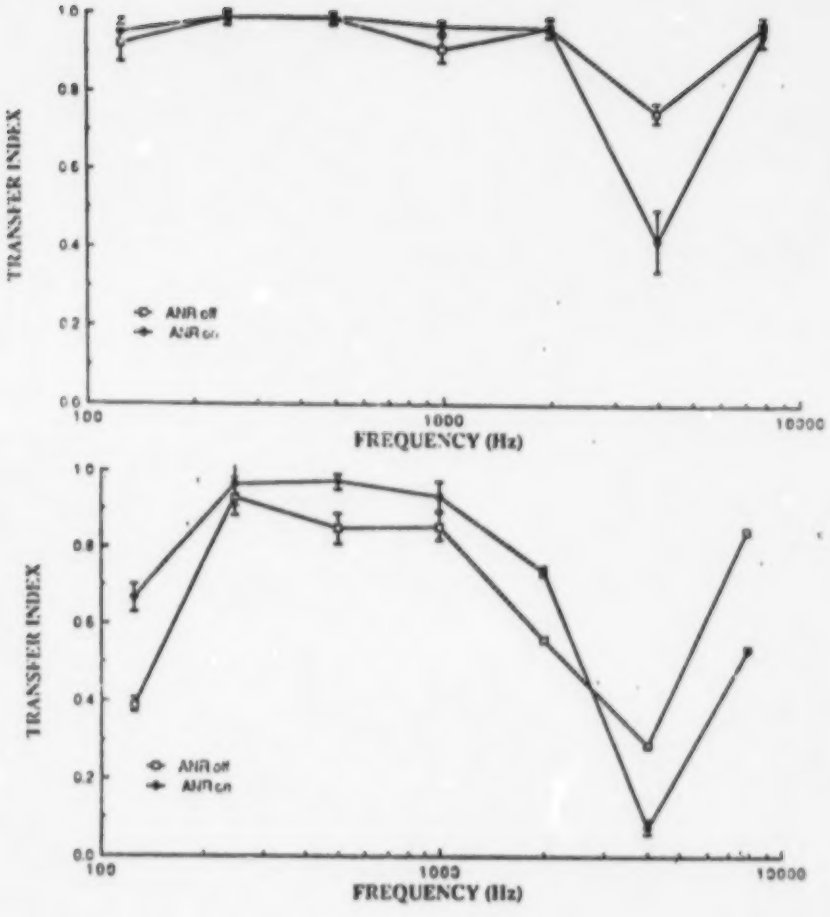

FIGURE 15. Octave-band Transmission Indexes (TI) of ANR in quiet (upper graph) and Sea King noise (lower graph), ANR *OFF* and *ON*, for an intercom signal level of 100 dBA measured at the ATF eardrum. The vertical bars represent one standard deviation above and below the mean.

APPENDIX A

REAL EAR AT THRESHOLD ATTENUATION (dB) OF THREE CURRENT PASSIVE FLIGHT HELMETS

	One-Third Octave-Band Centre Frequency (Hz)									
	63	125	250	500	1000	2000	3150	4000	6300	8000
I. RAF Mk 4 (After Rood (1978))										
Mean ($\bar{y}$)	15.9	12.3	13.1	26.8	34.3	33.2	39.2	43.5	49.2	51.5
S.D. (σ)	4.1	4.0	4.5	3.1	3.9	4.0	4.5	5.7	7.4	6.2
II. ALPHA (After Odell (1987))										
Mean ($\bar{x}$)		13.4	14.5	23.5	28.4	32.3	39.6	44.8	41.1	39.2
S.D. (σ)		5.6	6.5	6.1	4.4	6.2	8.9	8.2	7.6	9.7
III. CF 190A (After Odell (1987))										
Mean ($\bar{x}$)		13.2	11.0	22.7	25.6	30.0	43.1	44.6	39.2	37.4
S.D. (σ)		4.8	4.0	4.1	6.5	5.0	6.1	7.7	8.4	7.5

APPENDIX B

ONE-THIRD OCTAVE AND EQUIVALENT-RECTANGULAR PASS BANDS

Frequency (Hz)	One-Third Octave Band (Hz)	Equivalent Rectangular Band (Hz)‡
63	52.6 - 70.8	45.8 - 80.2
125	110.6 - 139.5	104.9 - 145.1
250	221.1 - 279.0	223.9 - 276.1
315	278.8 - 351.2	285.7 - 344.3
500	442.5 - 557.5	461.6 - 538.4
630	557.0 - 703.0	585.1 - 674.2
800	707.5 - 892.5	746.4 - 853.6
1000	884.5 - 1115.5	935.9 - 1064.1
1600	1409.5 - 1790.5	1503.1 - 1696.9

‡ After Moore and Glasberg (1983).